

# SCREENING ANALYSIS

## 1.0 Introduction

The purpose of the screening analysis is to identify and evaluate those design options that could improve distribution transformer efficiency and to determine which to evaluate in detail in the engineering analysis and which to evaluate no further during this rulemaking. The screening process includes consultations with interested parties to identify a list of design options for consideration. The screening analysis also discusses the criteria for eliminating certain design options from further consideration. By comparing the design options against these criteria, the Department eliminates from further analysis those options that are not sufficiently developed or have characteristics that make them technologically unsuitable for consideration in the rulemaking. The factors for screening design options are:

- Technological feasibility. Technologies incorporated in commercial products or in working prototypes are considered technologically feasible.
- Practicability to manufacture, install, and service. If mass production of a technology in commercial products and reliable installation and servicing of the technology could be achieved on the scale necessary to serve the relevant market at the time of the effective date of the standard, then that technology will be considered practicable to manufacture, install, and service.
- Adverse impacts on product utility or product availability to consumers.
- Adverse impacts on health or safety.

This document discusses various design options for improving the energy efficiency of distribution transformers and describes the reasons for eliminating any design option from consideration. At this stage of the proceedings, design options will be evaluated based on the factors described above as set forth in the Process Improvement (Interpretive) Rule. 61 FR 36974 (July 15, 1996). The design options that are not eliminated in this screening analysis will be considered in the engineering analysis.

## 1.1 Stakeholder Comments

The Department considers stakeholder participation a very important part of the process for setting energy conservation standards. The Department actively encourages the participation and interaction of all stakeholders at all stages of the process. Early and frequent interactions provides for greater and more productive interaction between DOE and stakeholders.

Comments received during and after the Distribution Transformer Framework Workshop, November 1, 2000, related to the screening analysis were limited in scope and primarily addressed the role of the screening analysis in the rulemaking. One issue, raised by ABB during the workshop, was related to screening out sole source technology. The DOE responded that it would not set standards based on sole source technology. ABB also commented that “pie-in-the-sky” technology (e.g., superconductors) should be screened out. The Natural Resources Defense Council (NRDC) responded that technologies often are more realistic than they initially appear. Comments received after the workshop related to the screening analysis were limited in scope. The National Electrical Manufacturers Association (NEMA) commented

that the screening analysis should be based on performance levels and not design technologies. NEMA also commented that superconducting winding and power electronics should be screened out.

## **2.0 DISCUSSION OF DESIGN OPTIONS**

A transformer is a device constructed with two primary components: a magnetically permeable core, and a conductor of low resistance material wound around the core. The transformer's function is to change alternating current from one voltage (primary) to a different voltage (secondary). It accomplishes this through an alternating magnetic field or "flux" created by the primary winding in the core, which induces the desired voltage in the secondary winding. The change in voltage is determined by the "turns ratio", or relative number of times the primary and secondary windings are wrapped around the core.

Distribution transformer losses are generally very small, in the vicinity of a few percent or less of the total power handled by the transformer. There are two main kinds of losses in transformers, no-load (core) losses and load (winding) losses. Basically, higher transformer efficiencies can be achieved by reducing transformer losses associated with these two assemblies, the core and windings. Core losses are a constant loss of energy, occurring continuously to keep the transformer energized and ready to provide power (even if the demand is zero). Winding losses on the other hand, increase with the square of the load (current is being drawn), and result from resistance in the windings.

Core losses are chiefly made up of two components, hysteresis and eddy current losses. Hysteresis losses are caused by the magnetic lag or reluctance of the core molecules to reorient themselves with the 60Hz alternating magnetic field applied by the primary winding. Eddy current losses are actual currents induced in the core by the magnetic field, in just the same manner that the field induces current in the secondary winding. However these currents can't leave the core, and simply circulate and become heat. In both instances, hysteresis and eddy currents losses result in core heat generation.

The second principal kind of loss, winding losses, occurs in both the primary and secondary windings when the transformer is called into service, subjected to a load. These losses, the result of resistive losses in both conductors, vary with the amount of load, the demand placed on the transformer.

It is technically feasible to design and manufacture energy efficient transformers using well-established and available engineering practices and techniques. A transformer design can be made more energy efficient by using lower-loss materials and/or optimizing the geometric configuration of the core and windings assemblies. Although the core and winding losses may appear to be independent components in the design of a transformer, they are not. Losses are coupled by the thermal power (heat) generated inside a transformer, a major design constraint. In addition to the core and winding (coil) assemblies, a transformer has additional parts which are not electromagnetic elements but still constrain the design of a transformer: the electrical insulation, insulating media (oil for liquid-filled transformers and air for dry-type transformers), and the enclosure (the tank or case). Both the core and winding have temperature limitations which if exceeded accelerate the aging process of the insulation and reduce the life of the transformer. Having set the insulation requirements, a transformer design can be varied with respect to both material and geometry within the constraints of size and impedance. Reducing the losses in a transformer is essentially a design trade-off issue -- more costly and lower loss

materials balanced against the cost of the electric losses. For a given efficiency level, the core and winding losses are inversely related; decreased losses in one generally are associated with increased losses in the other. Thus, there is a wide range of possible designs with different life-cycle costs for a given efficiency level. The engineering analysis promises to show that for a given efficiency level a wide range of designs is technologically feasible using common engineering practices and techniques currently being utilized.

A general overview of the loss reduction alternatives is shown in Table 1.

**Table 1 - General Loss Reduction Interventions**

Loss Reduction Interventions		No-Load Losses	Load Losses	Effect on Price
Decrease No-Load Losses	Use lower-loss core materials	Lower	No Change <sup>a</sup>	Higher
	Decrease flux density by increasing core CSA <sup>b</sup>	Lower	Higher	Higher
	Decrease flux density by decreasing volts/turn	Lower	Higher	Higher
	Decrease flux path length by decreasing conductor CSA	Lower	Higher	Lower
Decrease Load Losses	Use lower-loss conductor materials	No Change	Lower	Higher
	Decrease current density by increasing conductor CSA	Higher	Lower	Higher
	Decrease current path length by decreasing core CSA	Higher	Lower	Lower
	Decrease current path length by increasing volts/turn	Higher	Lower	Higher

<sup>a</sup>Amorphous-core materials would result in higher load losses because flux density drops, requiring a larger core volume.

<sup>b</sup>CSA = cross-sectional area.

The design options considered in the following sections are grouped in two categories. The first category, discussed in Section 2.1, contains design options to be used by DOE in the engineering and economic analyses. The second category, discussed in Section 2.2, contains design options that have been eliminated from further consideration using DOE's screening analysis criteria.

## 2.1 Design Options for the Engineering Analysis

All design options used in modern distribution transformer practice are considered viable options. For a specific efficiency level a wide range of designs is technologically feasible using several options: conductor materials for coils, core materials, variation of design dimensions, and construction techniques (see Table 2).

### 2.1.1 Conductor Materials

Aluminum, copper, and their alloys are presently used in both distribution and power transformer applications and are available for use in all standard wire sizes and foils. When the two materials are applied in exactly the same manner, copper has a higher electrical conductivity and about 40% lower resistive losses than aluminum. Eddy current losses, a major component of

core losses, are somewhat lower in aluminum due to higher resistivity. Compared to copper, aluminum is easier to form and work mechanically. Aluminum is also less expensive than copper, and is used in some designs as a cost-cutting option. Using aluminum at a lower current density ( $J$ ) or using it with a larger conductor cross sectional area, transformer windings can be built with essentially the same load losses. However, this has the effect of increasing core losses as a result of the larger frame size, greater winding space required for aluminum. It is common practice and an efficient design option to use copper in the high voltage (HV) windings and aluminum, at lower  $J$ , in the low voltage (LV) windings, even in very low-loss units. Aluminum is used in the form of foils to reduce eddy current losses. As in power transformer applications, units with high-loss evaluations may use bundled, transposed, and stranded conductors to further reduce an already-low eddy current loss component.

### **2.1.2 Core Materials**

Core materials available for distribution transformer applications are the following:

- High-silicon magnetic steels, both non-oriented hot rolled and oriented cold rolled
- Domain-refined grain oriented, high-silicon magnetic steels
- Amorphous (Metglas®) magnetic steels (wound core designs)

All of these core materials are presently used in distribution transformer cores at varying flux levels and lamination thickness. All commercially available high-silicon, cold rolled transformer steels, nominally designated M2-M6, and domain-refined or laser-scribed steels are available for use in all (both wound and stacked) core configurations; however, application of amorphous materials is presently a viable design option in wound core form only.

Transformer cores in the past had relatively high losses, since they were fabricated from thick laminates of non-oriented, low silicon magnetic steels. Modern transformer design practices have produced low-loss core materials that use silicon (~2-3%) and small amounts of other elements, are cold rolling, have improved laminar insulations, are in the form of thinner laminations, and are domain refined (e.g. laser-scribed steels).

Amorphous metal or Metglas® material allows the construction of a very low-loss core. Amorphous metal is extremely thin, has high electrical resistivity, and has little or no magnetic domain definition. Cores made from these materials exhibit 60-70% lower losses than other designs. Amorphous metal materials do have some drawbacks: they saturate at a lower flux level of 1.57 Tesla versus 2.08 Tesla for conventional materials, and they have higher excitation requirements. Being somewhat fragile, amorphous transformer designs cannot be packed as effectively into the winding window, and thus have a space factor of 85% versus 95-98% for other materials. The net effect of the lower flux density and higher space factor is a larger core with greater conductor losses and higher production costs. The use of amorphous materials also is constrained by having a single supplier, and one company holding exclusive patent rights to these materials.

### **2.1.3 Variation of Design Dimensions and Construction Techniques**

The engineering analysis will include, but is not limited to, the following design options: variation of current ( $J$ ) and flux density ( $B$ ), adjustment of volts per turn, voltage spacings, frame and coil dimensions, geometric shape, cooling channels (placement and number), insulating

materials, core types, and construction techniques. The application of computers in transformer design is well-established and widely used by nearly all manufacturers. Within the normal constraints as determined by basic insulation level (BIL), voltage rating, total impedance, temperature rise, weight, physical size, and overcurrent performance, all design options are available for the engineering analysis.

**Table 2 - Design Options Used in the Engineering Analysis**

Design Options	
Conductor Materials for Coils	
	Aluminum
	Copper
	Copper-Aluminum Alloys
Core Materials	
	Cold Rolled High Silicon (CRHiSi) Steel
	CRHiSi Domain Refined Steels
	Amorphous Materials in Wound Core
Variation of Design Dimensions	
	Flux Density (B)
	Current Density (J)
	Volts/Turn
	Voltage Spacings
	Frame/Coil Dimensions
	Shape
	Cooling Channels - Number and Location
	Insulating materials
	Core Type (Shell or Core Form either Stacked or Wound)
Construction Techniques	
	Core Cutting
	Core Stacking
	Core Lapping or Butting of Joints
	Coil Winding
	LV-HV Pattern

## 2.2 Design Options Eliminated from Further Consideration

The screening criteria for eliminating design options from further consideration are:

- 1) Technological feasibility.
- 2) Practicability to manufacture, install, and service.
- 3) Adverse impacts on product utility or product availability to consumers.
- 4) Adverse impacts on health or safety.

If mass production of a technology in commercial products and reliable installation and servicing of the technology could be achieved on the scale necessary to serve the relevant market at the time of the effective date of the standard, then that technology is considered practicable to manufacture, install, and service. If a technology is determined to have significant adverse impact on the utility of the product to significant subgroups of consumers, or if adoption of a technology results in the unavailability of any covered product type with performance characteristics (including reliability), features, sizes, capacities, and volumes that are substantially the same as products generally available in the U.S. at the time, it will not be considered further. If it is determined that a technology will have significant adverse impacts on health or safety, it will not be considered further.

DOE eliminated the following design options from further consideration because they do not meet the screening criteria as described in the individual discussions below:

- Silver as a Conductor Material
- High Temperature Superconductors
- Amorphous Core Material in Stacked Core Configuration
- Carbon Composite Materials for Heat Removal
- High Temperature Insulating Material
- Solid-State (power electronics) Technology

The reasons for excluding these design options from consideration in the engineering analysis are discussed below and summarized in Table 3.

### **2.2.1 Silver as a Conductor Material**

Silver has the highest electrical conductivity of normal metals at room temperatures. However, it is not considered a viable candidate for use as a distribution transformer conductor material because its lower melting point, lower tensile strength, and limited availability. Having a lower melting point than standard conductor materials requires impractical complex designs, constrained by lower operating temperatures. Its lower tensile strength also adds several complexities to the process of manufacturing transformers, as silver conductors can easily break during handling and manufacturing. Being a precious metal, it is not available in quantities necessary to support the distribution transformer manufacturing industry. Therefore, this design option is screened out from further consideration because of its impracticability to manufacture, install, and service (criterion 2).

### **2.2.2 High Temperature Superconductors**

In late 1987 a new class of high temperature superconducting (HTS) materials was discovered. These materials are superconducting (exhibiting zero direct current electrical resistance) at temperatures above the boiling point (77 K or -196°C) of liquid nitrogen at atmospheric pressure. Research and development (R&D) into applying these materials to power transformers has received worldwide funding. Extensive R&D programs are in place to develop practical HTS conductors exhibiting appropriate loss performance in time-varying magnetic fields that can be applied in real world applications. The application of low temperature superconducting (LTS) liquid helium cooled and HTS liquid nitrogen cooled superconductors for transformers has proven to be an elusive goal. LTS applications are physically possible but not feasible for commercial use, and some designs are not able to return to the superconducting state following a high fault current condition. For HTS, two demonstration power transformers have been built and at least two more are in various stages of design and construction. Current application constraints include unique conductors, unacceptable alternating current variation losses, and complex cryogenic support components. R&D continues in all these areas and DOE is funding efforts to overcome these technological barriers. Hence, HTS technology is not considered a viable loss reduction technology for distribution transformers now or in the foreseeable future and is excluded from further consideration based on technological feasibility (criterion 1).

### **2.2.3 Amorphous Core Material in Stacked Core Configuration**

While production capacity for materials is somewhat limited, amorphous materials are considered viable core materials for wound core applications, and are considered in the engineering analysis. Attempts to extend amorphous applications to stacked core applications have had limited success; they are not presently a viable design option for distribution transformers and have limited application to the larger dry-type transformer frames. Application of amorphous core material in stacked core configuration is not yet technically feasible and mass production of this technology in distribution transformers is not possible or viable at this time or at the effective date of this standard. Therefore, amorphous core materials in stacked core configuration are excluded from further consideration based on technological feasibility (criterion 1) and its impracticability to manufacture, install, and service (criterion 2).

### **2.2.4 Carbon Composite Materials for Heat Removal**

An example of a new material that may prove effective in future transformer applications is carbon fiber technology for heat removal. These materials are comparable to diamond in heat conduction and electrical insulation performance. Laboratory small non-distribution transformer prototypes using this technology have demonstrated about a 35% size and loss reduction. These results were achieved at the Naval Research Laboratory (see U. S. Patent 6,259,347 B1). Such results are impressive but large-scale application of this technology is several years away. Therefore, the use of composite materials to enhance heat removal is excluded from further consideration due to technological feasibility issues (criterion 1).

### **2.2.5 High Temperature Insulating Material**

Insulating materials continue to enjoy significant R&D in the transformer industry. The objective of these R&D efforts is to create insulation that operates at higher temperatures without affecting transformer life, and that conduct or transport heat out of the windings more effectively, while providing the same or higher dielectric performance. Increasing insulation performance results in smaller effective core and coil volumes, and therefore lower transformer losses. Since practical “high temperature, super insulation or composite heat removal techniques” systems are not commercially available, high temperature insulating material is excluded from further consideration due to technological feasibility issues (criterion 1).

### **2.2.6 Solid-State (power electronics) Technology**

Solid-State (power electronics) technology applied to transformers is a new technology in its early stages of development, not commercially available. A small bench test version has been built at Purdue University as a modeling exercise but no claims have been made about its efficiency or its application for distribution transformers. Therefore, solid-state (power electronics) technology is excluded from further consideration based on technological feasibility (criterion 1).

## **3.0 Results**

Based on the above discussion, the design options used in the Engineering Analysis are listed in Table 2, and those that have been eliminated from further consideration are listed in Table 3.



**Table 3 - Design Options Excluded from the Engineering Analysis**

Design Options with Exclusion Criteria	
Silver as a conductor material	
	Practicability to manufacture, install, and service
High Temperature Superconductors	
	Technological feasibility
Amorphous Core Material in Stacked Core Configuration	
	Technological feasibility
	Practicability to manufacture, install, and service
Carbon Composite Materials for Heat Removal	
	Technological feasibility
High Temperature Insulating Material	
	Technological feasibility
Solid-State (power electronics) Technology	
	Technological feasibility

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